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Photovoltaic thermal module concepts and their performance analysis: A review

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ABSTRACT

This paper presents a review of the available literature covering the latest module aspects of different photovoltaic/thermal (PV/T) collectors and their performances in terms of electrical as well as thermal output. The review covers detailed description of flat-plate and concentrating PV/T systems, using liquid or air as the working fluid, numerical model analysis, experimental work and qualitative evaluation of thermal and electrical output. Also an in-depth review on the performance parameters such as, optimum mass flow rate, PV/T dimensions, air channel geometry is presented in this study. Based on the thorough review, it is clear that PV/T modules are very promising devices and there exists lot of scope to further improve their performances. Appropriate recommendations are made which will aid PV/T systems to improve their efficiency and reducing their cost, making them more competitive in the present market.

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Contents

1. Introduction

Recent hike in oil prices has resulted in strong stimulation of research into renewable energy because such research can make major contributions to the diversity and security of energy supply, to the economic development and to the clean local environment. Renewable energy technologies currently supply 13.3% of the world's primary energy needs [1] and their future potential

Abbreviations: a-Si, amorphous-silicon; BIPV, building-integrated photovoltaic; c-Si, crystalline-silicon; COP, coefficient of performance; CPC, compound parabolic concentrator; CR, concentration ratio; pc-Si, polycrystalline-silicon; PV, photovoltaic; PV/T, photovoltaic/thermal; TMS, thin metal sheet.

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Nomenclature

A/A_C	ratio of heat transfer area to collector aperture area
A_C	PV/T collector area (m^2)
C_b	conductance of the bond between the fin and tube (W/m K)
C_p	specific heat of fluid (J/kg K)
d	outside tube diameter (m)
d_i	inside tube diameter (m)
F	fin efficiency
F'	collector efficiency factor
F_R	heat-removal factor
G	fluid mass flow rate per unit collector area (kg/s m^2)
G_T	solar irradiance (W/m^2)
h	heat transfer coefficient of fluid (W/m^2 K)
h_r	equivalent radiation coefficient (W/m^2 K)
k	thermal conductivity of the fin (W/m K)
Q_u	useful collected heat by collector (W/m^2)
T	temperature of PV module (K)
T_{ref}	PV module Reference temperature (K)
T_a	temperature of the ambient (K)
T_i	fluid inlet temperature (K)
T_f	average fluid temperature (K)
T_p	average plate temperature (K)
U_L	overall collector heat loss coefficient (W/m^2 K)

Greek symbols

δ	plate thickness (m)
η_{th}	PV/T thermal efficiency
η_{mp}	PV cell efficiency
$\eta_{mp,ref}$	maximum power point efficiency
$\mu_{P,mp}$	PV cell efficiency Temperature coefficient
$\tau\alpha$	transmittance–absorptance product

depends on exploiting the resources that are available locally and on overcoming the environmental challenges as well as winning public acceptance. Various forms of renewable energy depend primarily on incoming solar radiation, which totals about 3.8 million EJ per year. To harness the available solar energy resource effectively, the integrated photovoltaic combined thermal systems (PV/T) are especially attractive because the absorbed solar radiation is converted into electricity and heat which can be utilized simultaneously.

The main component of a photovoltaic/thermal (PV/T) system is a photovoltaic/thermal (PV/T) module, which is a combination of photovoltaic panel integrated to a solar thermal collector, forming one device that converts solar radiation into electricity and heat concurrently. PV/T modules have the ability to generate more energy per unit surface area than side by side PV panels and solar thermal collectors, at a lower production and installation cost. Because of its high efficiency per unit surface area, PV/T is particularly well suited for applications with both heat and power demand and with limited roof space available. In the Netherlands calculation done by ECN (Energy Research Centre of the Netherlands) [2] showed that it was possible to reduce the collector area by 40% with the use of PV/T collectors while generating the same amount of energy. Moreover, PV/T modules share the aesthetic advantage of PV. The incorporation of PV modules as part of the building envelope is a viable way of utilizing PV systems due to the combined provision of electrical power, heated air or hot water for use within the building. Large surfaces in the facade and roof of buildings are available and suitable for incorporating PV modules in them. Such incorporation has been referred as building-integrated PV (BIPV) technology and accounts for a significant portion in urban applications of PV systems in buildings.

2. PV/T development

The sun is the ultimate source for most of our renewable energy supplies and the direct use of solar radiation has a deep appeal to engineer and architect alike. Solar thermal collectors are used to convert solar radiation to thermal energy. In a thermal collector, a liquid or gas is heated and pumped, or allowed to flow through thermal convection, around a circuit and used for domestic or industrial heating. Photovoltaic cells are used to direct conversion of sunlight to electricity. The principal function of a PV cell is simple-silicon wafers convert the solar energy falling on them directly into electricity.

The most significant difference between solar thermal and photovoltaic system is that solar thermal systems produce heat and photovoltaic systems produce electricity. There are several methods to gather the solar energy and in a PV system most of the solar radiation that is absorbed is not converted into electricity. PV cells utilize a small fraction of the incident solar radiation to produce electricity and the remainder is turned mainly into waste heat in the cells, causing the increase of PV cell temperature hence the efficiency of the module drops. Cooling either by natural or forced circulation can reduce this PV cell temperature. An alternative to the PV cell is to use Photovoltaic thermal system (PV/T) (Fig. 1), where PV cell is coupled with heat extraction devices. The simultaneous cooling of the PV module maintains electrical efficiency at satisfactory level and thus the PV/T collector offers a better way of utilizing solar energy due to the increased overall efficiency. The attractive features of the PV/T system are:

- it is dual-purpose: the same system can be used to produce electricity and heat output;
- it is efficient and flexible: the combined efficiency is always higher than using two independent systems and is especially attractive in BIPV when roof spacing is limited;
- it has a wide application: the heat output can be used both for heating and cooling (desiccant cooling) applications depending on the season and practically being suitable for domestic applications;
- it is cheap and practical: can be easily be retrofitted/integrated to building without any major modification and replacing the roofing material with the PV/T system can reduce the payback period.

The concept of PV/T has been used and discussed for more than three decades by various researchers both experimentally and numerically. During the 1970s, the research on PV/T started, with the focus on PV/T collectors, with the main aim of increasing the overall energy efficiency. Domestic application was regarded as the main market. Initially the focus was on glazed collectors, both air type and liquid type, but soon the idea of an unglazed PV/T collector combined with a heat pump also received attention.

Like the thermal solar collectors, PV/T systems are categorized also according to the kind of heat-removal fluid used, hence PV/T water system and PV/T air system are common types, for water and air heat-removal fluids, respectively. PV/T water systems are more efficient than PV/T air systems [3], due to high heat conductivity and hence high heat capacity, high density-resulting in a high volume transfer. But use of water requires more extensive modifications to enable water-tight and corrosion-free construction.

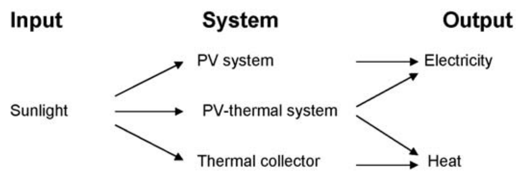

Fig. 1. Comparison between PV, PV/T and solar thermal systems.

Hence, natural or forced air circulation through an air channel on the PV rear or top or both surface, is the simplest mode to extract heat from PV modules.

Apart from the different heat extraction methods, the performance of the PV/T system depends on the PV module type as well. PV module can be constructed with crystalline-silicon (c-Si), polycrystalline-silicon (pc-Si) and the newly developed thin films of amorphous-silicon (a-Si) types of cells. Crystalline-silicon has by far the largest market share of all PV technologies. Although c-Si are highly efficient, they are expensive because of the slow manufacturing processes, laborious and energy intensive. A number of approaches to reduce the cost of c-Si cells and modules have been under development during the last 20 years or so. The newly developed thin films of a-Si have a significant market share since they are much cheaper to produce and are cost effective for low temperature applications.

The photovoltaic integrated thermal systems can be widely used for various applications. Large-scale applications include power generation, where the PV/T system can either be mounted on the rooftops of houses or in large fields connected to the utility grid. These systems are not only promising but also provide clean, safe and strategically sound alternatives to current methods of electricity generation. Grid-connected PV power offers consumers both economic and environmental advantages. Where utility power is available, consumers can use a grid-connected PV system to supply a portion of the power they need while using utility-generated power at night and on very cloudy days. The heat extracted can be utilized to meet the heating load of the domestic/commercial buildings.

A vast majority of autonomous or stand alone PV/T systems are used to supply electricity in regions with no grid, no telephone coverage, and often with difficult accessibility. There are no moving parts, so the system's lifetime is very long and it is virtually maintenance free. It is more popularly used for rural electrification. Further, to increase solar yield and electricity production, researchers have attempted to use solar trackers and concentrator PV/T systems, best for both small- and large-scale applications. The primary reason for using concentrators is to enable using less solar cell material in a PV system. A concentrator makes use of relatively inexpensive materials such as plastic lenses and metal housings to capture the solar energy shining on a fairly large area and focus that energy onto a smaller area, where the solar cell is. Sometimes fins are attached on the back of the photovoltaic panel to increase the heat transfer from the PV solar cell to the air to further enhance the efficiency of the system.

Substantial amount of research has been carried out in improving the overall efficiency of the PV/T systems. Various techniques have been adopted to analyze its impact on the system performances with the main focus on the electrical efficiency. Typically, commercially available PV modules are only able to convert 6–18% of the incident radiation falling on them to electrical energy, with the remainder lost by reflection or as heat. However, a small portion of the heat is "sunk" into the cells which results in a reduction in their efficiency. Though the short circuit current of PV cells is not strongly temperature-dependent, it tends to increase due to increased light absorption. This is attributed to the fact the semiconductor materials used in the cells experience a temperature dependant decrease in the given band gap.

In order to reduce the impact of temperature on PV cell performance, various modifications have been attempted in the heat recovery channel of the PV/T system. In this present paper, emphasis will be on the various module aspects and techniques to improve heat transfer of the PV/T systems. Recommendations for further improvement in the overall efficiency of PV/T system, is also presented in the respective sub-sections. A detailed description of hybrid PV/T solar systems is included in a recently published Roadmap [4,5], where many aspects regarding technology, present status and future perspectives of these solar energy conversion systems are presented.

3. PV/T devices

PV/T devices can vary in design for various applications, ranging from PV/T domestic hot water systems to ventilated PV facades and actively cooled PV concentrators. The markets for both solar thermal and PV are growing rapidly and have reached a very substantial size. For PV/T a similar growth can be expected, since the technical feasibility is proven and can be integrated with other domestic applications. PV/T has broad range of application, that is, it is not only suitable for domestic hot water heating (glazed PV/T collectors), but also for commercial buildings (ventilated PV to preheat ventilation air during winter and to provide the driving force for natural ventilation during summer). Hence, the market for PV/T might even be larger than the market for thermal collectors.

The thermal demand can be covered by choosing appropriate PV/T system. There exist various forms of PV/T system which depend on the type of PV module as well as its design, type of heat-removal fluid (water/glycol or air) and on the concentration of the incoming radiation.

Therefore, PV/T products can be classified as:

- Liquid PV/T collector;
- Air PV/T collector;
- Ventilated PV with heat recovery;
- PV/T concentrator.

Irrespective of the type of collector, the absorber of each PV/T collector may have a glass cover over the absorber to reduce the thermal losses. If such a cover is present, the collector is referred to as "glazed", otherwise as "unglazed".

- Glazed collectors have smaller thermal losses, especially at higher collector fluid temperatures. For medium to high temperature applications, this results in a much higher annual thermal yield.
- Glazed collectors result in high stagnation temperatures that may be critical for certain types of PV encapsulant (risk of yellowing and delamination) and the glazing makes the module more sensitive to hot spots. In addition, bypass diodes may get overheated due to the additional insulation. Reflection losses at the glazing further reduce electrical performance. Increased temperature levels lower the electrical yield.

In summary, whether the collector should be glazed or not, it is important to find a good balance between the increased thermal yield on one hand, and the reduction in electrical yield and the issues related to possible degradation on the other hand. The relationship is given in Table 1.

3.1. Liquid PV/T collector

In order to improve energy performance of the photovoltaic system, much effort has been spent on research and development of the hybrid PV/T technology using water as the coolant. The

Table 1
Recommendation of the collector type based on the type of demand.

Demand	Recommendation
Water	
High temperature	Use glazed liquid collector. Also, an unglazed collector can be used if PV/T has to be integrated to a heat pump.
Low temperature	To meet only summer demand, use unglazed liquid collector. On the other hand, to meet both summer and winter demands, use glazed liquid collector; an unglazed collector can be chosen if PV/T has to be integrated to a heat pump.
Air	
High temperature	Use glazed air collector or unglazed collector. Ventilated PV can be used as a heat source if PV/T has to be integrated to a heat pump.
Low temperature	To meet only summer demand or for the place receiving high irradiation in winter, use unglazed air collector or ventilated PV. On the other hand, to meet both summer and winter demands, use glazed air collector; an unglazed collector can be a choice if PV/T has to be integrated to a heat pump.

liquid PV/T collectors are similar to conventional flat-plate liquid collectors; an absorber with a serpentine tube or a series of parallel risers is applied, onto which PV has been laminated or glued as an adhesive epoxy joint.

Two common configurations used in PV/T systems are: “The parallel plate configuration”, and “The tube-in-plate configuration”. Prakash [6], Huang et al. [7], Tiwari et al. [8,9] have worked on the parallel plate design, while Zondag et al. [10], Chow [11,12], Kalogirou [13], Huang et al. [7], Tiwari and Sodha [14] have carried out an in-depth study on tube-in-plate design. Within the first works on PV/T water system, Bergene and Lovvik [15] initially conducted a theoretical study on PV/T water system composed of flat-plate solar collector with solar cells. They suggested that their proposed system might be useful particularly to preheat the domestic hot water.

More recently, Zondag et al. [16] grouped the design concepts of water-type PV/T collectors into four main types: sheet-and-tube collectors, channel collectors, free-flow collectors, and two-absorber collectors. All these quoted collector types are designed for pump (forced) circulation. Based on numerical analysis it was suggested that providing channel below the transparent PV module could be the best option from the collector efficiency point of view [12]. Nevertheless, from the viewpoint of good overall performance and structural simplicity, the single-glazing sheet-and-tube hybrid PV/T collector is regarded as the most promising design.

Dubey and Tiwari [17] designed an integrated photovoltaic (glass-to-glass) thermal (PV/T) solar water heater system and tested it in outdoor conditions of India. Similarly, Erdil et al. [18] constructed and tested a hybrid PV/T system for energy collection at geographical conditions of Cyprus, where they used water as the cooling fluid. It was reported that the payback period for their proposed modification was less than 2 years which made their hybrid system economically attractive.

Chow et al. [12] developed a numerical model of a photovoltaic-thermosyphon collector system using water as a working fluid and verified the model accuracy by comparing with measured data. The energy performance of the collector system was examined, through reduced-temperature analysis and the study was further extended to analyze the performance of the system in the “hot summer and cold winter” climate zone of China. The numerical results were found to be very encouraging, and according to them the equipment is capable of extending the PV application potential in the domestic sector.

Apart from the above study, Chow et al. [19] also carried out analytical simulation to investigate the annual performance of building-integrated photovoltaic/water-heating system for Hong Kong climate and found that annual thermal and cell conversion efficiencies were about 37.5% and 9.39%, respectively. Based on the results, they confirmed that PV/T systems could be applicable even to hot-humid regions.

Though the liquid collectors have proven to be technically feasible, economical feasibility is yet questionable. Compared to air heating PV/T system, not much of developments are seen in the literature, on liquid-heating systems due to its inherent limitations such as: additional cost of the thermal unit pipes for the water circulation, and the inherent freezing problem of working fluid when used in low temperature regions, etc.

3.2. Air PV/T collector

The PV/T air collectors are similar to a conventional air collector heater with a PV laminate functioning as the top or bottom cover of the air channel. PV/T air collectors are cheaper than the PV/T liquid collectors because of the flexibility that conventional PV modules can be easily converted to a PV/T system, with very few modifications. PV/T air collectors can either be glazed or unglazed. In general, air collectors are mostly applied if the end-users have a demand for hot air, space heat, dry agricultural products, or to condition the indoor air (air cooling).

Presently, air heating systems are mainly designed to directly use the air for space heating. However, the opportunity for this application depends directly on the market share of air heating systems, which is low in most countries. A niche market is given by preheating of ventilation air for large volume buildings (stores, sport halls, schools and other commercial buildings) where temperatures in the range of 15–25 °C are desirable. With the very same air systems, hot water preparation is often possible through an air/water heat exchanger, which is generally done during the summer season in order to increase the overall performance of the system.

The application of air as a heat transport medium compared to air, has significant advantages along with few inevitable disadvantages.

Advantages:

- No freezing and no boiling of the collector fluid.
- No damage if leakages occur.

Disadvantages:

- Low heat capacity and low heat conductivity, which result in a low heat transfer.
- Low density, which results in a high volume transfer.
- High heat losses through air leakage.

As the heat transfer in the air-cooled PV/T system is much more critical than in the liquid cooled PV/T system, it is important to model the heat transfer properly. Eicker [20] presented an overview of entrance-effect heat transfer relations for air collectors, showing a variation of about 10% in average Nusselt number when integrated over the entrance length and reported that for a sufficiently wide channel, the hydraulic diameter should be twice the channel height.

The impact of air flow induced by buoyancy and heat transfer through a vertical channel heated from one side by the PV module

on the PV/T performance was investigated numerically and experimentally by Moshfegh and Sanberg [21,22]. The study reports that the induced velocity increases the heat flux non-uniformly inside the duct and its impact depends on the exit size and design. More analysis and modeling on passively cooled PV/T air systems continue to appear [9,14,23–26] and a substantial amount of research has been specifically carried out [27–32] to improve heat transfer to the air of both buoyancy-driven and forced air flow systems. Their studies were focused generally on channel geometry, creation of more turbulence in the flow channel and increasing of the convective heat transfer surface area in the channel. Most of these studies used simulation model for their experimental work where the PV module was simulated by a heated foil.

Similar to the liquid collectors, various types of solar air systems exist and an overview had been given by Hastings and Morck [33]. The main concepts on air-cooled PV/T systems were presented in the works of Kern and Russel [34], Hendrie [35], Florschuetz [36], Raghuraman [37], Cox and Raghuraman [38]. The exclusive theoretical aspects of PV/T systems with air as the heat extraction fluid are detailed by Bhargava et al. [39], Prakash [6], and Sophian et al. [40].

3.3. Ventilated PV with heat recovery

In conventional PV facades or PV roofs, an air gap is often present at the rear in order to allow the air to cool the PV by means of natural convection (ventilated PV). If this heat can be recovered from the PV and be used in the building, then the same PV is considered to function as a PV/T collector. Such PV facades, apart from providing electricity and heat, have additional benefits as well:

- A PV facade may limit the thermal losses by infiltration. Also the PV facade has the advantage to shield the building from the solar irradiance, thereby reducing the cooling load. Hence, such facades are especially useful for retrofitting poorly insulated existing offices.
- If there is no demand for the generated heat, then air collectors and PV facades can use their buoyancy induced pressure difference to assist the ventilation,
- Facade integration of PV has an additional cost incentive of substituting expensive facade cladding materials.

Because of their easier construction and operation, hybrid PV/T systems with air heat extraction are more extensively studied, mainly as an alternative and cost effective solution to building-integrated PV systems (BIPV). Test results from PV/T systems with improved air heat extraction were given by Ricaud and Roubeau [41] and from roof integrated air-cooled PV modules by Yang et al. [42].

Posnansky et al. [43], Ossenbrink et al. [44] and Moshfegh et al. [45] have worked extensively on the building-integrated PV/T systems. Later, Brinkworth et al. [46–48], Moshfegh and Sandberg [21] and Krauter et al. [49] presented design and performance studies regarding air type building-integrated hybrid PV/T systems. In addition, Eicker et al. [50] gave monitoring results from a BIPV PV/T system that operated during winter for space heating and during summer for active cooling.

Yet another comprehensive examination of PV and PV/T in built environments was presented by Bazilian et al. [51]. The study has highlighted the fact that PV/T systems are well suited to low temperature applications. Furthermore, they noted that the integration of PV systems into the built environment could achieve "a cohesive design, construction and energy solution". Finally, they suggested that there is a need for further research in the said field, before combined PV/T systems become a successful commercial reality.

The building-integrated photovoltaics is going to be a sector of a wider PV module application and the works of Hegazy [52], Lee et al. [53], Chow et al. [54] as well as Ito and Miura [55] had given interesting modeling results on air-cooled PV modules. Recent work on building-integrated air-cooled photovoltaics includes the study on the multi-operational ventilated PVs with solar air collectors [56], the ventilated building PV facades [57–59] and the design procedure for cooling air ducts to minimize efficiency loss [26].

According to Elazari [60], smaller size PV and PV/T systems, using aperture surface area of about 3–5 m^2 and water storage tank of 150–200 l, could be installed on one family houses. They have suggested that, larger size systems of about 30–50 m^2 and 1500–2000 l water storage are more suitable for multi-flat residential buildings, hotels, hospitals and various food processing industries.

Charalambous et al. [61] suggested that the building-integrated PV/T collectors are most suited for low climatic conditions to lower the temperature of the PVs and supply the hot air for space heating. Battisti and Corrado [62] investigated the EPBT (energy payback period) for a conventional multi-crystalline building-integrated with PV system (retrofitted on a tilted roof) for the yearly global insolation on a horizontal plane as 1530 kWh/m^2 year in Rome. The study reports that EPBT gets reduced from 3.3 years (stand alone system) to 2.8 years by integrating the PV to the building. Despite these improvements, commercial application of PV/T air collectors is still marginal, but it is expected to be wider in the future where many building facades and inclined roofs will be covered with photovoltaics.

PV facades are already well established and are largely identical to PV/T facades. Hence, replacing expensive facade cladding materials by PV facades, it is expected that the costs on module level will be low compared to all other applications. However, on system level the situation may be different; since PV facades are often unglazed, the temperature levels that can be reached are limited, and the costs of the additional infrastructure required may outweigh the benefits of the use of this heat, so it is essential to come up with alternative low cost system designs.

A difference between ventilated PV with heat recovery and PV/T collectors, the PV/T system is typically designed for a specific building and is not manufactured as a standardized system. Due to the current strong link between this type of PV/T and specific building projects, it is very difficult for a non-specialist architect to provide this option for a specific project. However, this situation may change since several institutes and manufacturers are making an effort to standardize these systems [63].

3.4. PV/T concentrator

The combination of solar radiation concentration devices with PV modules is up to now the most viable method to reduce system cost, replacing the expensive cells with a cheaper solar radiation concentrating system. By concentrating, a (large) part of the expensive PV area is replaced by cheap mirror area, which is a way to reduce the payback time. This argument is the driving force behind PV concentrators. Concentrating photovoltaics present higher efficiency than the typical ones, but this can be achieved only when PV module temperature is maintained as low as possible [64]. The concentrating solar systems use reflective and refractive optical devices and are characterized by their concentration ratio (CR). Concentrating systems with CR > 2.5 must use a system to track the sun, while for systems with CR < 2.5, stationary concentrating devices can be used [65]. The distribution of the solar radiation on the absorber surface (PV module) and the

temperature rise of it are two problems that affect the electrical output. The uniform distribution of the concentrated solar radiation on the PV surface and the suitable cooling mode contribute to an effective system operation and the achievement of high electrical output. PV/T absorbers can be combined with low, medium or high concentration devices, but low CR PV/T systems have been mainly developed so far.

Reflectors of low concentration, either of flat type [66–68] or of Compound Parabolic Concentrator (CPC) type [64,69–74] have been suggested. Tripanagnostopoulos et al. [75] suggested diffuse reflector to increase both electrical and thermal output of PV/T systems. Garg et al. [68] presented the simulation study of the single-pass PV/T air heater with plane reflector. Garg and Adhikari [69,71] reported the performance analysis of a hybrid PV/T collector with integrated CPC troughs. Both cases indicated that the total efficiency with reflector was slightly higher compared to the systems without concentrators. Due to the increase in solar radiation, the average plate as well as solar cell temperatures had shown a sharp rise. Hence, the system performance in terms of electrical efficiency was low, for the fact that the cell performance is dependent on its temperature. Othman et al. [64] designed a new double-pass photovoltaic thermal air collector with CPC and fins. They observed that electricity production in a PV/T hybrid module decreased with a rise in temperature of the air flow.

A simple low concentrating water cooled type PV/T collector of the building-integrated type was recently investigated by Brogren and Karlsson [76]. It incorporates PV/T string modules with low cost aluminum foil reflectors with a CR of 4.3 times. Regarding medium concentration, PV/T systems based on linear parabolic reflectors [77] or linear Fresnel reflectors [78] had been investigated. Although concentrators of low or medium CR are interesting devices to be combined with photovoltaics, 3D Fresnel lens or reflector type concentrators have been recently developed, aiming at the market of concentrating photovoltaics. The concept of combined linear Fresnel lenses with PV/T absorbers has also been used for applications such as indoor space heating as well lighting [79].

Coventry [77] developed the "CHAPS" (combined heat and power solar) PV/T collector. It involved a parabolic trough with CR to be 37 for mono-crystalline-silicon cells and a two-axis tracking system. At the back of the cells a tube with water and antifreeze was attached to collect most of the generated heat produced.

Even though the PV efficiencies of concentrated PV/T systems are high, up till now the market share for such systems has been negligible, which is mainly due to the fact that these systems are rather bulky, disqualifying them for many PV applications. Also, since CR requires tracking, it makes building integration impossible. Furthermore, not all climates are suitable for high ratio concentration, because it depends on the amount of direct irradiation received. In the aesthetic point of view, the concentrating systems provide different reflections and optical effects, which are unusual to the built environment and also they might prevent such systems from being placed visibly in the facade construction. The best option may be to install the concentrator on a horizontal roof (e.g. PV/T systems with booster reflector in parallel rows).

One more additional point worthy to note is, though the small cell area allows the use of more efficient and expensive PV material, the combination of glazing and reflectors increases the stagnation temperature which may in turn lead to degradation of materials. For electrical performance, the uniformity of the irradiance may be compromised, increasing mismatch losses. However, this drawback might be overcome to certain extent by using diffuse reflectors.

4. PV/T module concepts

In a PV cell, part of the solar spectrum does not contribute to the electricity production. Photons with energy lower than the band gap do not have enough energy to create photon–hole pairs and could in principle fully contribute to the generation of heat. This generation can take place either in the cell or outside the cell if the cell material does not absorb light at these wavelengths. The position of heat generation in the device determines the possible PV/T device geometries. In most concepts all heat is generated in one place in the device. In a two-absorber PV/T collector, however, part of the heat is generated outside the PV cells [80].

4.1. Different types of PV/T modules

Most of the PV/T systems reported in the literature follow one of the four following conceptual designs. A basic PV/T collector, shown schematically in Fig. 2, typically consists of a PV module on the back of which an absorber plate (a heat extraction device) is attached. In this, a PV panel is attached on the top of the metallic absorber plate.

A more effective heat transfer is obtained when the mean distance between heat generation and heat collection is minimal. Hence, in the second type of design shown in Fig. 3, the liquid flows over the PV panel. On the other hand, in the third type of design (Fig. 4), the liquid is allowed to flow beneath the PV panel through multiple channels to withdraw the heat generated by the PV cells. These channels are formed using plastic sheet by extrusion. This geometry is better suited to withstand water pressures in the channels than in the case of one broad channel shown in Fig. 3. Plastics, however, have a relatively large coefficient of thermal expansion. Hence, it becomes challenging to ensure proper connection between channel material and PV cells.

In the fourth type of PV module concept, the PV cells can be made transparent, either through the use of gridded-back contacts or by interspaced cells; two-absorber geometry can be applied, as shown in Fig. 5. One of the main advantages of this concept is that a lower mean PV cell temperature is maintained, compared to geometries with heat and electricity generation in one plane. But the complexity of the two-absorber geometry makes the module difficult to manufacture [80].

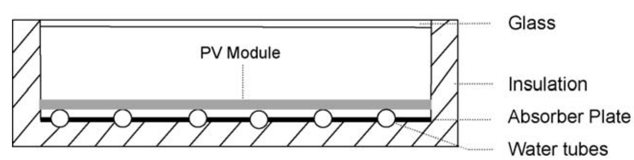

Fig. 2. Cross-section of a basic PV/T collector.

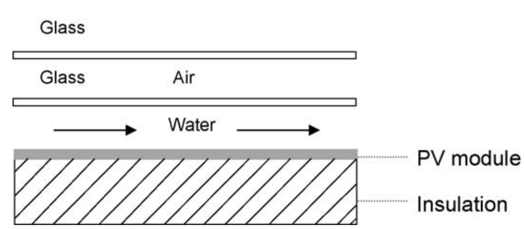

Fig. 3. PV/T concept with liquid flowing on top of the PV module.

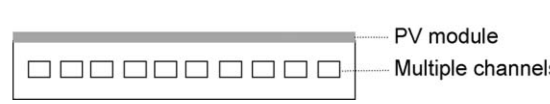

Fig. 4. Channel PV/T concept with liquid flow beneath the PV cells.

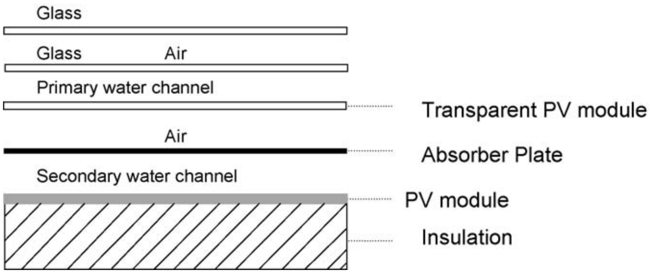

Fig. 5. Two-absorber PV/T model.

4.2. Summary of researchers' experience and recommendations

Tripanagnostopoulos et al. [81] tested the PV/T system for three design modes (Fig. 6), i.e. with an heat exchanger (HE) element placed on PV rear surface (Mode A), in the middle of an air channel (Mode B), and on an air channel opposite surface (Mode C). They found that the placement of HE at PV module's rear surface gave optimum system thermal performance, both for water and air circulation, with the fact that it had higher positive impact on water circulated system. They suggested that Mode A is an effective combination for the PV/T system when engaged with the dual heat extraction operation.

Later, Tripanagnostopoulos et al. [82] compared the performance of two types of air-cooled PV/T system: (i) a commercial PV module was used with float glass provided on the front and black tedlar on the rear surface of PV module (reference system); (ii) a new pc-Si PV module was used with transparent tedlar on the front and float glass on the rear surface of PV module (modified system). Their study concluded that the newly fabricated modified system reduced PV temperature by about 6 °C which resulted in an increase of electrical efficiency.

Similar to Tripanagnostopoulos et al. [82], Tiwari and Sodha [83] also carried out research on PV/T system and studied the performance on four different configurations. Their results showed that the outlet air temperature, back surface module temperature and solar cell temperature for glazed hybrid PV/T without tedlar is slightly higher than the values for glazed hybrid PV/T with tedlar. They also found that the rate of useful thermal energy obtained from PV/T system for glazed hybrid PV/T systems was higher than unglazed hybrid PV/T systems. Irrespective of the PV/T system with or without tedlar, the study reported that, there is a significant increase in overall efficiency of the hybrid PV/T system and it can be more pronounced if more small modules are connected in series, than as one single system for the chosen length.

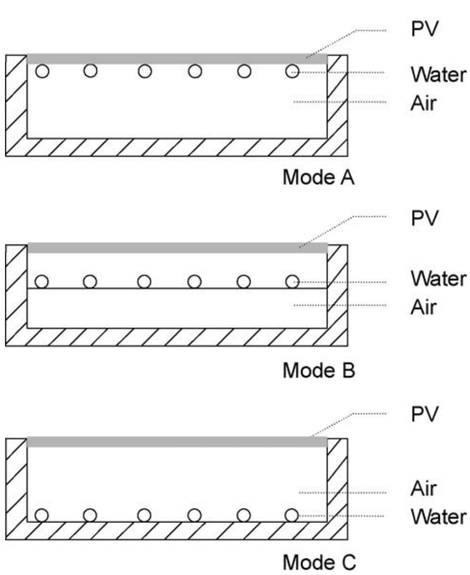

Fig. 6. Three modes of unglazed PV/T modules.

Joshi et al. [84] tried two novel methods to investigate their impact on PV/T system performance.

- Case 1: PV module was integrated to glass-to-tedlar. In this case, solar radiation is absorbed by solar cell as well as EVA (ethylene vinyl acetate) and it is then conducted to base of the tedlar for thermal heating of air flowing below it.
- Case 2: Conventional PV module with glass-to-glass was used. In this case, solar radiation is absorbed both by solar cell and black surface of the insulated base. The flowing air underneath the base is heated by convective heat both from black surface as well as heat conducted from solar cell.

They found the overall thermal efficiency in the order of 43.4–47.4% for glass-to-glass and 41.6–45.4% for glass-to-tedlar case. It can be noticed clearly that there is a significant increase in the performance of a glass-to-glass than in the glass-to-tedlar air collector. This is due to the fact that in glass-to-glass design, it is possible to extract more thermal energy from the black surface by the air that is being circulated in the duct. Hence, it is recommended to have the absorber surface to be selectively coated to increase its absorption as well as reduce reflective losses. This will in turn aid better heat transfer to the air in the duct.

To further confirm the advantages of using glass-to-glass PV/T system, Dubey et al. [85] carried out experiments by integrating the above discussed PV module with and without a duct. They considered four different configurations of PV modules for their study which were defined as: (i) Case A – glass-to-glass PV module with duct, (ii) Case B – glass-to-glass PV module without duct, (iii) Case C – glass-to-tedlar PV module with duct, and (iv) Case D – glass-to-tedlar PV module without duct. It was found that the glass-to-glass PV modules with duct gives higher electrical efficiency as well as the higher outlet air temperature compared to the other configurations. The percentage differences between electrical efficiency of glass-to-glass and glass-to-tedlar type PV modules with and without duct were found 0.24% and 0.086%, respectively.

Unlike to the above described works [81–85], Erdil et al. [18] used the cooling medium in front rather than on the rear surface of the PV module. The cooling fluid (i.e. water) was circulated between the glazing and the module and was stored in a storage tank as pre-heated water for domestic applications. By comparing the time plot of thermal energy collected and the electrical energy loss (which was due to absorption and reflection of radiation while passing through the glazing and water), they noticed that thermal energy gain was more than 50 times higher than the electrical energy loss. Even though electrical energy is more versatile than thermal energy, but the ratio of gain to losses is very high. Therefore, it is worth trying to utilize the thermal energy generated by the PV surface.

5. Performance analysis

A PV/T collector basically combines the functions of a flat-plate solar (thermal) collector and those of a photovoltaic panel.

5.1. Theory of flat-plate solar collectors

The thermal performance of the flat-plate solar collector is described by the Hottel–Whillier–Bliss [86] thermal efficiency equation. The equation is used in the design of solar liquid and air

heaters and has found extensive application in the simulation and evaluation of solar systems.

The useful heat output of a flat-plate solar collector in terms of the absorber plate temperature is given as:

$$Q_u = F A_C[G_T(\tau\alpha) - U_L(T_p - T_\alpha)] \tag{1}$$

where F is the fin efficiency which can be estimated using the following expression:

$$F = \frac{\tanh\left[\sqrt{(U_L/K\delta)((s-d)/2)}\right]}{\sqrt{(U_L/K\delta)((s-d)/2)}} \tag{2}$$

Because the absorber plate temperature T_p varies both across and along the plate, the collector heat gain can be expressed in terms of average fluid temperature, which is relatively easily controlled and measured during testing and operation. Hence, heat gain equation based on the fluid average temperature T_f given as:

$$Q_u = F' A_C[G_T(\tau\alpha) - U_L(T_f - T_\alpha)] \tag{3}$$

where F' is the efficiency factor which varies for different types of heat transport fluids (liquids or gases).

$$F' = \frac{1/U_L}{S\{(1/U_L[(s-d)F + d) + (1/C_b) + (1/h\pi d_i)\}} \quad \text{for water} \tag{4}$$

$$F' = \frac{1}{1 + (U_L/(h_f A/A_C + (1/(1/h_r + 1/h_f))))} \quad \text{for air} \tag{5}$$

Instead of using average fluid temperature, it will be much more convenient to express the heat gain of a solar collector in terms of the fluid inlet temperature, T_i. Expressing the heat gain in terms of the fluid inlet temperature, the expression can be rewritten as:

$$Q_u = F_R A_C[G_T(\tau\alpha) - U_L(T_i - T_\alpha)] \tag{6}$$

where F_R is the heat-removal factor which is defined in relation to the efficiency factor (F'):

$$\frac{F_R}{F'} = \frac{GC_P}{U_L F'}\left[1 - \exp\left(-\frac{U_L F'}{GC_p}\right)\right] \tag{7}$$

Hence, the steady-state thermal efficiency (η_{th}) of a conventional flat-plate collector is calculated by

$$\eta_{th} = \frac{Q_u}{G_T}. \tag{8}$$

5.2. Theory of photovoltaic modules

Electrical efficiency of the photovoltaic panel depends on its temperature and it is reduced when the temperature increases. This is evident from the following equation, which demonstrates the dependence of the efficiency of a photovoltaic cell, η_{mp}, on its temperature [87]:

$$\eta_{mp} = \eta_{mp,ref} + \mu_{P,mp}(T - T_{ref}) \tag{9}$$

In the above expression, $\eta_{mp,ref}$ is the maximum power point efficiency of the photovoltaic collector at the reference temperature (T_{ref}), $\mu_{P,mp}$ is the temperature coefficient of photovoltaic efficiency (generally a negative number), and T is the photovoltaic collector temperature. According to above equation, each PV panel produces not only electrical energy but thermal energy as well, when solar radiation falls on it. Improving the electrical efficiency by reducing the photovoltaic collector's temperature, as well as utilizing the thermal energy produced, constitute the basic idea behind the development of a hybrid PV/T system.

5.3. Analytical models of PV/T collectors

Analytical expressions have been derived in terms of design and climactic factors to predict the instantaneous thermal efficiency for the present configuration. Within the earlier works on theoretical analysis of PV/T system, Florschuetz [36] did an extension of Hottel–Whillier equation to model PV/T collectors by adopting simple modifications to the conventional parameters used in the original model and all other existing relations in predicting the collector performance were unaltered. He developed a simple linear relationship to predict the effect of cell operating temperature on the PV/T system efficiency. Raghuraman [37] also carried elaborate numerical model both for liquid and air type PV/T flat-plate collector and found that the system with air as the working fluid could achieve a thermal efficiency of about 42%.

Jones and Underwood [88] also derived an expression for PV module temperature in terms of irradiance and ambient temperature. The unsteady-state model derived in their study was based upon the theoretical description of module temperature described by Schott [89]. According to Jones and Underwood, there were several parameters that were responsible for the PV module electrical efficiency reduction such as packing factor (PF), ohmic losses between two consecutive solar cells and the temperature of the module. Among the above mentioned factors, increasing the packing factor could improve the efficiency considerably by withdrawing the thermal energy.

To predict the working temperatures of the PV module and the heat-removal fluid during periods of fluctuating irradiance or intermittent fluid flow in a transient condition, Chow [11] developed an explicit dynamic model based on the control-volume finite-difference approach for a single-glazed flat-plate water-heating PV/T collector. He used a thin adhesive layer made of an EVA layer and Tedlar layer to fix the PV plate on to the absorber plate. He found two key manufacturing defects in PV/T collectors: (i) the imperfect adhesion between the PV plate and the absorber plate, and (ii) the imperfect bonding between the absorber plate and the metallic tubes. He has reported a maximum combined efficiency of a perfect collector could be over 70% and might decrease to less than 60% for a low-quality collector.

Yet another physical model was developed by Bergene and Lovvik [90] to make quantitative performance predictions of a hybrid photovoltaic/thermal system. Their model was purely based in analyzing different modes of heat transfer such as conduction, convection and radiation encountered in the energy transfer process. This model could predict the amount of heat that can be drawn from the system as well as the (temperature-dependent) theoretical power output. Their proposed model predicted the performance of the system fairly well with system efficiencies, both thermal and electrical, being about 60–80%.

Sopian et al. [40] also developed a steady-state model to analyze thermal performance of single-pass and double-pass PV/T air systems. The study shows that double-pass PV/T air system had better efficiencies (both the thermal and combined) compared to the single-pass (typical) system due to the efficient cooling of the PV cells.

An extensive investigation of the thermal, electrical, hydraulic and overall performances of flat-plate PV/T air collectors was carried out by Hegazy [52]. In his analysis, he considered four designs with the air flowing either over the absorber or under it and on both sides of the absorber in a single-pass or in a double-pass fashion. Based on the performance results, he suggested that the design, in which air was allowed to pass on both sides of the absorber, was the most suitable design for converting solar energy into low-quality heat and high quality electrical energy. Also such system was simple to be built by local craftsmen in the rural areas of developing countries.

Recently, following the work of Hegazy [52], in 2005 Othman et al. [64] designed and fabricated a prototype double-pass photovoltaic thermal solar air collector with CPC with fins. The system was tested for its performance over a wide range of operating conditions, and reported that the electricity production decreased with increasing temperature of the air flow, implying that the air temperature should be kept as low as possible. However, if hot air is required for some end-uses, a trade-off between maximizing electricity production and producing hot air of useful temperature is necessary.

Sandnes and Rekstad [91] developed an analytical model for the PV/T system which could simulate the temperature development and the performance of both thermal and photovoltaic units. They combined a polymer solar heat collector with single-crystal silicon PV cells in a hybrid energy-generating unit that simultaneously could produce low temperature heat and electricity. They experimentally tested the PV/T unit to determine its thermal and photovoltaic performance, in addition to the interaction mechanisms between the PV and thermal energy systems. The simulation results were in agreement with the experimental data, and their results showed that by pasting solar cells onto the absorbing surface, the solar energy absorbed by the panel could be significantly reduced (10% of incident energy). According to them, this was attributed due to lower optical absorption in the solar cells compared to the black absorber plate [reduced ($\tau\alpha$) for the collector]. In addition, there was an increased heat transfer resistance between the absorbing surface and the heat carrier fluid introduced in the cell/absorber plate interface which resulted in a reduction in the collector heat-removal factor, F_R.

Tiwari et al. [9] derived an analytical expression for the overall efficiency (electrical and thermal) in order to evaluate the performance of the PV module integrated with air duct for composite climate of India. They found a fair agreement between their experimental and theoretical results for back surface, outlet air and top surface temperatures with correlation coefficient of about 0.97–0.99 and root mean square percent deviation of about 7.54–13.89%. The overall efficiency of hybrid PV/T system was to be increased by about 18% due to thermal energy output in addition to the electrical energy production.

Apart from the above mentioned work, Joshi and Tiwari [92] also studied the performance of a hybrid PV/T parallel plate air collector for four different climatic conditions and evaluated exergy analysis for cold climatic condition of India (Srinagar). They observed the instantaneous energy and exergy efficiency of PV/T air heater varied between 55–65% and 12–15%, respectively which were very close to the results predicted by Bosanac et al. [93]. They found an increase of about 2–3% exergy due to thermal energy output in addition to its 12% electrical output from PV/T system.

The impact of climatic conditions on the PV/T system was further investigated by Dubey and Tiwari [17]. They designed and tested an integrated combined system of a photovoltaic (glass-to-glass) thermal (PV/T) solar water heater in outdoor condition for three typical days during the month of February to April, 2007. They also derived an analytical expression to characterize the performance of PV/T flat-plate collector as a function of design and climatic parameters. The developed thermal model was validated with their experimental results and reported that when flat-plate collector is covered partially with PV module it resulted in better thermal and average cell efficiency. The modified system could attain an increase in the instantaneous efficiency by about 33–64% mainly due to the increase in glazing area.

The above mentioned theoretical model was used to evaluate the performance of the modified PV/T system under four distinct climatic conditions of New Delhi, India. The analytical model could predict monthly average electrical efficiency by considering different weather conditions of New Delhi for glass-to-glass type PV module with and without duct and was found to be 10.41% and 9.75%, respectively [85]. The glass-to-glass type PV module with duct gave higher efficiency than the glass-to-tedlar type. This is because the radiation falling on non-packing area of glass-to-glass module is transmitted to the air flow in the duct, whereas in case of glass-to-tedlar entire radiation is absorbed by the tedlar. The reported results are in agreement with the other researchers' investigations [11,16].

As an extension of the above mentioned study, Dubey and Tiwari [94] evaluated the theoretical performance of partially covered flat-plate water collectors connected in series. The performance was simulated for five different locations (New Delhi, Bangalore, Mumbai, Srinagar, and Jodhpur) in India reflecting different seasons. The study reported that the collectors partially covered by PV module were beneficial in terms of annualized uniform cost if the primary requirement of user is thermal energy yield. On the other hand, if the primary requirement of user is electrical energy yield then the fully covered collectors are beneficial. The results also showed that the outlet water temperature increased considerably from 60 to 86 °C as the number of collectors connected in series increased from 4 to 10. The useful thermal energy yield was about 4.17 to 8.66 kWh and electrical energy yield increased from 0.052 to 0.123 kWh depending on the number of collectors. This type of configuration is very useful in the urban and rural areas, where the hot water and electricity are required simultaneously along with some carbon credits. The study predicted that, if the proposed type was installed even only in 10% of the total residential houses in Delhi, the total carbon credit earned by PV/T water heater in terms of thermal energy was USD $144.5 million per annum and in terms of exergy was about USD $14.3 million per annum, respectively.

An attempt was made by Joshi et al. [95] to analyze the performance characteristics of a PV and PV/T system based on energy and exergy efficiencies. First the "fill factor" was determined experimentally to evaluate the effect of the fill factor on the efficiencies. The energy and exergy efficiencies of the PV and PV/T systems were evaluated for a typical day (27th March) in New Delhi and found that the energy efficiency varied from a minimum of 33% to a maximum of 45%, respectively. The corresponding exergy efficiency for PV/T system was found to be 11.3–16%, while for PV it varied from a minimum of 7.8% to a maximum of 13.8%.

5.4. Modeling and simulation

Several researchers have carried out simulation studies which were based on a simple energy balance of each component of the PV/T system, in order to identify and analyze various performance parameters. Garg and Adhikari [96] developed a simulation model for PV/T air heating collectors to analyze the effect of various design and operational parameters on the performance of the system. Parametric studies show that the system efficiency increases with increase in collector length, mass flow rate and cell density, and decreases with increase in duct depth for both configurations. It has also been observed that for larger values of duct depth the percentage decrease in performance of the double-glass configuration is smaller than for the single-glass configuration. As material cost increases by increasing the number of glass covers, collector length, cell density, duct depth and mass flow rate, final selection of design parameters of a PV/T system must be based on the cost-effectiveness of the system by minimizing the life cycle cost of the system.

A novel heat pump system was proposed by Jie et al. [97] in which the PV/T collector was coupled to a solar assisted heat pump and worked as an evaporator. They developed mathematical model to analyze the complex energy conversion processes and performed a numerical simulation based on the distributed

parameters approach. The Simulation results were validated with their experimental data. Results indicated that the photovoltaic solar assisted heat pump (PV-SAHP) as a combined unit could yield better coefficient of performance (COP) and photovoltaic efficiency than being treated as separate units. The system COP of the PV-SAHP could attain a maximum value of about 8.4 while the average value was around 6.5 along with an average photovoltaic efficiency of about 13.4%.

Extensive work of PV/T systems have been initiated and carried out at the University of Patras by Kalogirou and Tripanagnostopoulos [98]. They had constructed and tested hybrid PV/T systems consisting of pc-Si and a-Si PV modules combined with water heat extraction units, which were modeled and simulated with the TRNSYS program. Simulation study was carried out for three locations at different latitudes, Nicosia (35°), Athens (38°) and Madison (43°). The results showed that the electrical production of the system employing polycrystalline solar cells was more compared to amorphous ones, but the solar thermal contribution was slightly lower. The economics of the systems show that, though amorphous-silicon panels are much less efficient than the polycrystalline ones, they have better cost/benefit ratios.

Cox and Raghuraman [38] explored two main areas: (i) increasing the solar absorptance and (ii) reducing the infrared emittance of PV/T collectors with the use of computer simulation to determine their effectiveness and interaction on overall system performance. The work focused on the air type collectors employing single-crystal silicon PV cells. Simulation results showed that when the total collector area is covered by about 65% with PV cells, providing a selective absorber actually reduces the thermal efficiency when used with a gridded-back cell. The optimum combination for an air PV/T was found to consist of gridded-back PV cells, a nonselective secondary absorber, and a high-transmissivity/low-emissivity glass cover above the PV cells.

5.5. Experimental work

Various PV/T prototypes were designed and tested by several researchers, with an objective to develop an efficient system which could yield higher electrical efficiency, and satisfactory thermal output. He et al. [99] constructed and tested a water-type PV/T system with a polycrystalline PV module on an aluminum-alloy flat-box absorber which functioned as a thermosyphon system. The results showed that if the working water initial temperature was same as the daily mean ambient temperature, then the maximum thermal efficiency could reach 40%, which is about 0.8 times higher than that of a conventional solar thermosyphon collector system. This product design is simple and has a good potential for serving the domestic market.

Robles-Ocampo et al. [100] constructed and studied experimental model of a PV/T hybrid system with bifacial PV module to enhance the electric energy production. Further, in order to make use of both active surfaces of the bifacial PV module, they designed and fabricated an original water-heating planar collector with a set of reflecting planes. The hybrid system implemented with a bifacial module produced higher amount of electrical energy than a conventional PV/T system and the estimated overall solar energy utilization efficiency for the system was in the order of 60%, for which the electrical efficiency turned out to be 16.4%.

Aiming to low cost improvements of building-integrated air-cooled hybrid PV/T systems, Tripanagnostopoulos et al. [101] tested experimental models consisting of three modifications in the air channel. That is, the modified system was designed and tested for the following modifications: (i) air channel depth was varied, (ii) inserted fins/tubes in the air channel, and (iii) a selectively coated flat-plate was suspended in the air channel. The results of the modified system were compared with the reference system. It consisted of air channel with 15 cm depth. The comparative study was carried out both for vertical and inclined positions, corresponding to building facade and inclined roof PV integration modes. Based on the results, they suggested a simple and efficient heat extraction mode. That is, providing a roughened opposite channel surface with a thin metallic sheet (TMS) inside air channel could serve as a low cost system improvement.

In addition to the above studies, Tripanagnostopoulos et al. [81] further designed and fabricated a PV/T system with dual heat extraction operation, which could use water as well as air as the cooling fluid. The proposed PV/T system was aimed to be used either for water or air heating, depending on thermal needs of the application and climactic conditions of a region. Their experimental model consisted of a pc-Si PV module which had been integrated to an air channel, in which the heat exchanger element was carefully designed for flexibility in boosting inside the air channel. This improved system when combined with a booster diffuse reflector, could achieve an increase in total energy output by about 30%.

A practical and efficient system particularly suitable for PV installations on buildings was investigated by Tripanagnostopoulos et al. [82]. Two types of PV/T prototypes, one with a commercial pc-Si PV module (reference system), and a newly fabricated pc-Si PV module with transparent tedlar on the front and normal glass on the back of PV surface (modified system) were investigated. The systems were tested in vertical position for both natural and forced air circulation as well as stagnation (no air flow) conditions. Their results showed that their suggested modifications could satisfactorily cool PV module and improve PV/T system's energy performance.

Further, the possibility of generating electricity and heat energy from a commercial PV module, adopted as a PV/T air solar collector with either forced or natural airflow in the channel, was demonstrated by Tonui and Tripanagnostopoulos [31]. They constructed two identical prototype models using commercial pc-Si PV panels having a rated power output of 46 Wp, as absorber plates and an air channel of depth 15 cm attached at the rear surface of each module. The systems were mounted at a tilt angle of 40° (approximate optimum tilt angle for Greece). In order to augment the heat transfer, certain modifications such as suspending a thin flat metallic sheet (TMS) in the middle of the air channel or providing fins at the back wall of an air duct were tested for their impact on thermal output. The suggested modifications lowered the back wall temperature considerably compared to the reference system. Comparing the TMS and fin systems, the TMS system reduced the back wall temperature by about 5–3 °C for forced and natural flow conditions, respectively. For the same tested conditions, fins could reduce the back wall temperature by only about 2 °C for both forced and natural flow conditions. The TMS system presented lower values since the metal sheet shielded the back wall from 'seeing' directly the rear surface of the PV module, hence lowering the radiation heat exchanged between them.

The pumping powers for the above discussed three configurations were relatively less and were in agreement with the simulation results presented by Choudhury and Garg [102]. The additional power required by the modified systems were about 0.54 and 0.51 mW for TMS and fin systems, respectively. The typical power produced by the PV modules was about 35 W. Hence, the required additional power is negligible enough that it does not (less than 1%) to degrade its electrical output power by appreciable amount. The use of fin system is ideal for high latitude regions where the heat gain can be exploited in winter; on the other hand, the TMS is suitable for low latitude and tropical countries, because the system can maximize both the improved heat gain as well as its additional wall-shading effect.

In order to evaluate the overall performance of hybrid PV/T air collector under forced mode of operation, Tiwari and Sodha [83] carried out experiments for four different configurations such as, unglazed and glazed PV/T air heaters, with and without tedlar. The results showed that for glazed PV/T system irrespective of the provision of tedlar, the temperature of the outlet air, back surface of module as well as solar cell was significantly higher than the unglazed system, which was due to reduction in top loss coefficient. They also noted that the solar cell temperature for single module significantly increased in the case of the two-module system due to an increase in the inlet temperature of the second module. However, outlet air temperature increased marginally.

A hybrid system composed of a PV module and a solar thermal collector was experimentally studied by Erdil et al. [18]. The system mainly consisted of a module and a 4 mm thick glass plate cover which created a cavity. In order to avoid breaking of the glass plate due to high pressure developed in the cavity, a vent pipe provided at the outlet to enable the trapped air to escape. A similar problem was reported by Bakker et al. [103] and was solved by using an 8 mm thick glass plate to withstand the water pressure in the channels. The thermal energy gain for a 5 h period was about 1.4 kWh per day from each hybrid module. The 5 h period used in their calculation reflects minimum sunny hours per day in Cyprus [104]. Therefore, daily about 2.8 kWh thermal energy could be stored as pre-heated water for domestic utilization at the expense of 11.5% electrical energy loss. This loss, however represents only 1% of the 7 kWh energy that is consumed by a typical household in northern Cyprus.

Joshi et al. [84] studied the performance of unglazed hybrid PV/T glass-to-glass system for composite climate of New Delhi and compared with g lass-to-tedlar (PV/T) system for the forced mode of operation. In glass-to-glass PV/T air collector, absorber plate (blackened surface) was used instead of tedlar. In this case, more radiation transmitted from glass got absorbed on the black surface compared to tedlar surface. Hence, more thermal energy was available in the black surface. They found the electrical efficiency in both cases varied between 9.5% and 11% for a given day. This might be because of the fact that, the heat (thermal energy) removal from the back surfaces in both cases was quicker than the heat absorbed by the same at a given time. The thermal equivalent of electrical efficiency for both cases was same and range between 26.4% and 30.5%, while the thermal efficiency varied between 15.7% and 18.3% (glass-to-glass system) and 13.4% and 16.5% (glass-to-tedlar system), respectively. The thermal efficiency of glass-to-glass PV/T air collector was higher because its outlet air temperature was slightly higher than glass-to-tedlar system.

Solanki et al. [105] carried out experiments on a PV/T solar air heater system under indoor conditions. The experimental system consisted of three PV modules (mono-crystalline-silicon cells) of glass-to-tedlar type, each rated at 75 Wp having 0.45 m width and 1.2 m length and were mounted on a wooden duct. The study reported that the thermal, electrical and overall efficiency of the solar heater obtained at indoor conditions was 42%, 8.4% and 50%, respectively. These results were in agreement to the results obtained by other researchers for outdoor conditions [9].

6. Techniques to increase PV/T performance

There are numerous methods of enhancing the performance of PV/T air collectors such as the use of fins attached to the PV rear surface, corrugated sheet or wire mesh in the air channel or providing air circulation on both front and rear surfaces of the PV module.

Elements of several geometry can be placed between PV module and opposite channel wall, as well as on the back wall, by which air heat extraction can be effected more efficiently [32]. Roughening the opposite channel wall with ribs or/and using wall surface of high emissivity, which is considerably a low cost air heating improvement has also been adapted (Fig. 7a). In addition, corrugated sheet inside the air channel along the air flow can be attached on PV rear surface as well as on the opposite channel wall surface (Fig. 7b). An alternative modification is to put light weight pipes along the air flow in the air channel, with slight elasticity to ensure satisfactory thermal contact with PV rear surface and channel wall (Fig. 7c). These pipes are heated by conduction, convection and radiation from PV rear surface which can contribute to air heat extraction, avoiding the undesirable increase of opposite channel wall surface temperature.

Tripanagnostopoulos et al. [31,106,107] have made extensive studies to improve the heat transfer kinetics in the air channel of a

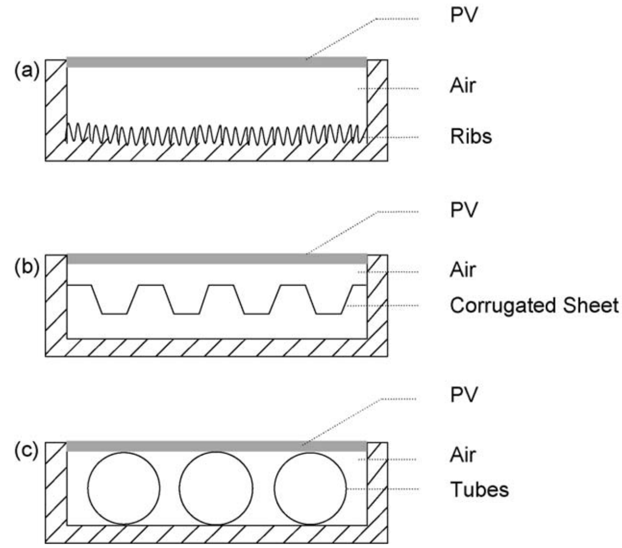

Fig. 7. Improvement of heat extraction of the PV/T air system with (a) ribs, (b) a corrugated sheet and (c) tubes.

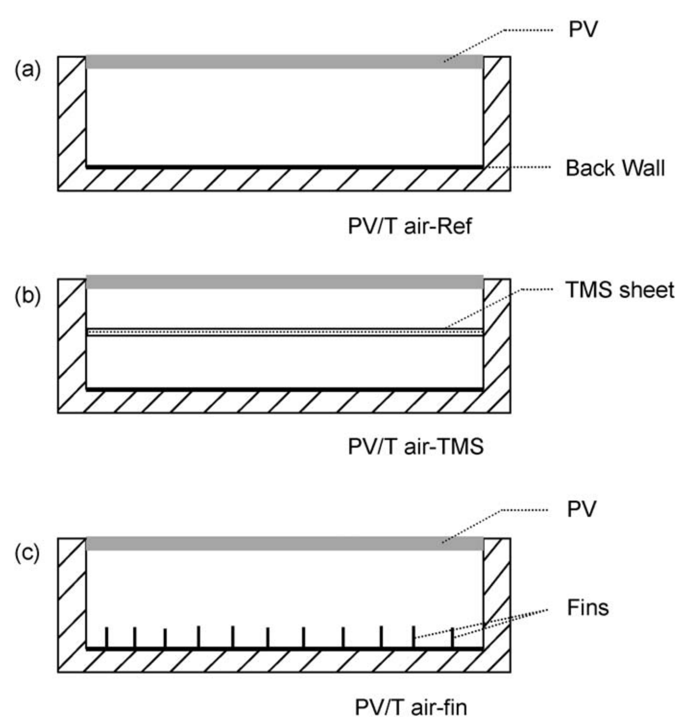

Fig. 8. Cross-sectional view of PV/T air collector models.

PV/T system. They have investigated the performance improvement modifications by using either finned back wall or thin flat metal sheet suspended in the middle of a PV/T air system to achieve higher thermal output and to aid PV cooling so as to keep the electrical efficiency at acceptable level. The cross-sectional views of their models are shown in Fig. 8. The models resemble convectional air collectors with the PV module as absorber plate. The system consisted of a simple air channel attached behind the PV module and for the improved systems they modified the channels by suspending a thin flat aluminum metal sheet in the middle of the air channel or by attaching rectangular profile fins on the opposite wall to the PV rear surface.

They have also suggested [106] to attach fins at the back wall as it is easier compared to attaching them at the back of the PV module which may require special features in the production of PV modules. Their suggested methods are simple to manufacture since both metal sheet and fins can be made from locally available cheap material and their incorporation in the middle or on opposite wall of the air channel are straight forward presenting more practical designs for the PV/T air collectors as well as ensuring low cost. Their applied techniques modify the duct hydraulics by lowering the hydraulic diameter, resulting in an increase in convection heat transfer coefficient and as well as the heat transfer surface area in the air channel. The net result is that more heat is transferred to air stream in the duct, creating higher stack in turn effecting high flow rate. Hence, the discussed modified systems performs better in terms of PV cooling as well as heat producing compared to the conventional types.

Their study [101] further shows that, when fins were attached on to the opposite air channel (of 15 cm depth) surface, with their flat vertical surfaces facing parallel to air flow, resulted in an increase in the heat exchanging surface area of the air channel. Fins of 1.5 and 4 cm of π profile using aluminum and galvanized iron, respectively, were used to form fin plate elements. The fins were positioned such that their vertical surfaces were parallel to the airflow, resulting in an increase in the heat exchanging surface area in the air channel. Further, the fins were selectively coated to improve emissivity on the thermal performance of the system. It was observed that larger the fin area, higher the temperature drop experienced at the PV module surface. Typically, the values were about 2–4 °C for a fin profile of 4 cm.

In addition to the above modifications, experiments were also carried out for both unglazed and glazed PV systems [106,107]. The results show that though the additional glazing improves the heat production it lowers the electrical efficiency of a PV/T collector. Othman et al. [64] have also confirmed that by attaching fins on the back of the photovoltaic panel, the heat transfer to the air as well as the overall efficiency of the system was enhanced.

Apart from using fins in the air channel duct, attempt was made to use metallic cylindrical tubes, using 0.5 mm thick aluminum sheet, to study the geometrical effect on the heat transfer mechanism [101]. Tubes were installed along the air channel pressed fit by PV rear surface and opposite wall surface of the air channel duct. For the given duct width, two tubes were used instead of three, in order to have low weight, cost and pressure drop. The study showed that though the temperature drop at the PV laminate surface is not much higher compared to the system using fins, it has better advantage since the back wall temperatures are much lower. Hence, using tubes in air channel duct has better implication for BIPV.

In addition to the above described modifications, Tripanagnostopoulos have carried out [101] performance studies by suspending a thin aluminum sheet (0.1 mm thick) in the middle of the air channel parallel to the PV laminate. This modification had better performance results compared to the other two discussed techniques. Using a simple metallic sheet instead of several fins

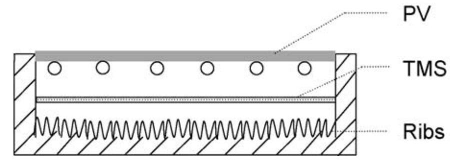

Fig. 9. Cross-section of the modified PV/T dual solar systems provided with TMS and ribs.

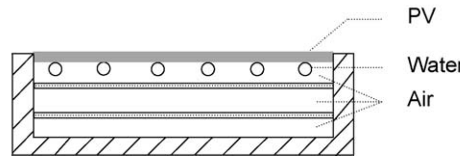

Fig. 10. Modified PV/T dual systems provided with two TMS.

has additional advantages such as, having higher heat transfer area, flexibility of coating the surface facing the PV laminate with a selective coating having high emissivity and the opposite side (lower part) of the surface facing the back wall with low-emissivity, to affect higher heat transfer rates.

Further, ribs of about 5 mm were formed on the opposite air channel wall, with an aim to combine the advantages of TMS and fin (shown in Fig. 9) [32], where the formation of ribs stimulates the performance of small fins. The ribs were further painted black to increase the heat transmittance by radiation from TMS back surface to air channel wall. This method is particularly promising and cost effective not only in terms of heat transfer, but also the fabrication, installation and material costs are much lower for the above mentioned simple plate geometry compared to other designs.

Confirming the improvement of system's thermal performance using metallic plate inside the air channel, Tripanagnostopoulos et al. [81] also extended using the said modification to the PV system (discussed in Section 4.2), in which the heat exchanger surface was integrated beneath the PV laminate. In the study, instead of using single sheet, two metallic plates (Fig. 10) were used to affect an increase in the heat transfer area by four folds. The study showed that the system could obtain a maximum thermal efficiency of about 45% and 55% for air heat extraction and water heat extraction mode, respectively.

Later, Tripanagnostopoulos et al. [82] placed TMS in the middle of the air channel in their modified PV module with tedlar front/normal glass back system to investigate whether the suggested modifications contribute to satisfactory PV cooling. They found that the interposition of a TMS in the middle of air channel in PV/T system had only a small effect in lowering PV module temperature. Even though it had lesser impact on electrical efficiency, this low cost modification enhanced the thermal efficiency of the system. These air-cooled modified PV/T systems are especially useful for building applications at locations in colder climates, as the heated air could be used for building space heating and for applications at locations with warmer climates the heated air could be used for space cooling by promoting natural ventilation.

To the above modified system, Tripanagnostopoulos et al. [81] attempted to incorporate flat diffuse reflector and was tested outdoor conditions for performance determination. They suggested to place stationary flat diffuse reflectors from the higher part of PV modules of one row to the lower part of PV modules of next row. This installation could ensure an increase in solar input on PV modules throughout the year with a significant increase in electrical and thermal output. They proposed the use of cost effective diffuse reflectors made of aluminum as they do not contribute to electrical efficiency drop, but provide an almost

uniform distribution of reflected solar radiation on PV module surface.

The reflector was tracked to achieve a 35% additional solar radiation from the diffuse reflector on the surface of the used PV module, and the CR was about 1.35 (a mean value of a stationary reflector–solar system combination). Experimental results showed a significant increase in thermal output for both heat extraction modes, achieving 75% for water (from 55%) and 60% for air (from 45%) circulation. These results confirm the advantage of using PV/T system with low concentration diffuse reflector making this combination most cost effective for horizontal building roof installations.

In an attempt to increase the radiation intensity on the PV module, Othman et al. [64] used CPC to increase the radiation falling on array of solar cells. Fins were also attached to the back side of the absorber plate to improve heat transfer to the flowing air. The results showed that the combined efficiency varied from 39% to 70% at mass flow rate of 0.015–0.16 kg/s for a given radiation intensity of about 500 W/m^2. They also observed that the experimental results were slightly higher than the predicted results which might be due to the effect of infrared radiation released by tungsten halogen lamps during the test.

In summary, modified PV/T systems could be considered practical and cost effective, suitable for building integration, contributing to both thermal and electrical demand of the system. It should be noted that additional glazing improves the heat production but lowers the electrical efficiency of a PV/T air collector [61,106,107]. In general, the above discussed studies show that electricity production in a PV/T hybrid module decreases with increasing temperature of the airflow, implying that the air temperature should be kept as low as possible. A trade-off between maximizing electricity production and producing hot air of useful temperatures is thus necessary. The simultaneous use of hybrid PV/T, fins, TMS, and diffuse reflector has a potential to significantly increase in power production and reduce the cost of photovoltaic electricity.

7. Future prospectus of PV/T system

The feasibility of the PV/T system will be dependent upon its technical and economical competitiveness with respect to other alternatives. The technical feasibility can be evaluated by comparing the electrical module efficiency and thermodynamic efficiency of such systems with those of the conventional ones, while the economic feasibility (energy metric analysis) can be tested by balancing the capital cost of the solar system against the savings in conventional fuel costs. As the economic feasibility is heavily dependent on the financial parameters based on some assumptions (e.g. the inflation rate of conventional fuel costs), it is certain that the viability of such solar systems will be more pronounced when the environmental costs of conventional electricity production are factored in.

As referred in earlier sections, several studies (both theoretical and experimental) shows that most of the systems could only achieve a maximum thermal efficiency of about 60% for air cooled and a slightly higher for water cooled PV/T system. The reduction in thermal efficiency might be due to reflection losses (since PV surfaces are not spectrally selective), and also due to the fact that the heat resistance between the absorbing surface and the heat transfer medium is increased because of the additional layers of material (e.g. tedlar). Hence, it is necessary to keep all layers between the PV panel and the absorber as thin as possible. It should be pointed out that several researchers [83–85] have confirmed to use glass instead of tedlar, as tedlar becomes a barrier for extracting thermal energy, in turn reducing both the electrical and overall efficiency of the system.

Poor thermal contact was also reported to be a problem by Sudhakar and Sharon [108] who found a temperature difference of about 15 °C between PV laminate and water output temperature. Hence, the objective of future research should aim to optimize the air channel geometry of the PV/T system and to simulate the PV/T collector characteristics, and further investigate the influence of various heat transfer promoters on the cell temperature of the PV module for different operating conditions. It is also essential to establish an analytical expression for the electrical efficiency of the PV module with and without air flow as a function of climatic and design parameters, which can be derived based on a detailed energy balance of each component of the chosen configuration.

For the case of PV/T liquid collectors, though the sheet-and-tube design performs efficiently, the channel plate constructions may provide interesting ways of further increasing the heat transport, provided that the channels are made sufficiently thin. For unglazed PV/T water collector, heat pump can be integrated to the PV/T system as it may be a promising development for the future. However, electrical consumption should be taken into account in the system's evaluation as its value is substantial for the case of heat pump. For the PV/T air collectors, some additional low cost heat transfer techniques could be investigated. Example, selectively coated inserts or fins in the air duct which could aid swirl flow can be attempted and air channel geometry could be optimized accordingly.

These suggested techniques would modify the duct hydraulics by lowering the hydraulic diameter and it would result in increasing convection heat transfer coefficient as well as the heat transfer area in the air channel. The net result would be more heat which could be transferred to air stream in the duct, creating higher stack effect leading to high flow rate. Therefore, these effects would aid better PV cooling and heat production. Any method that improves the performance even marginally would go a long way in improving the economics of such operating systems.

In addition, to make solar energy devices more attractive for potential applications, it is essential to develop a thermal model of integrated photovoltaic and thermal solar system, which could be used to analyze the overall system performance under various climatic as well as design conditions. Literature shows that there exists 1D, 2D and 3D dynamic models for a PV/T system [7,10,11,13] and that the simple 1D steady-state model for computing daily yield from PV/T system performs almost well as more time consuming 2D and 3D dynamic models [10]. Hence, one can derive an analytical expression for the temperature of PV module and the air (heat-extracting fluid) based on energy balance of each component of the proposed integrated air-cooled system.

8. Conclusion

The possibility of generating electricity and heat energy from PV/T solar collector with either forced or natural flow (using water or air) is demonstrated by various researchers. PV/T systems contribute immensely towards energy savings and mitigation of energy supply of buildings and consequently lower CO_2 emission among other social benefits. This paper covers a thorough review on latest module aspects of the various techniques that had been attempted in improving the overall performance of the PV/T system. The choice of technique depends on the location and its application which dictates the usage of appropriate design considerations. The review shows that, hybrid PV/T system systems are especially suitable to regions with cold climate since PV/T systems integrated to building-integrated applications lower the temperature of the PV's with air and can supply the hot air for space heating. However, based on the overview of research conducted to date, it is apparent that there is still a large amount of work that needs to be undertaken in terms of design aspects before

PV/T systems can be successfully implemented and integrated into domestic and commercial applications. With an optimal design, PV/T systems can supply buildings with 100% renewable electricity and heat in a more cost-effective manner than separate PV and solar thermal systems and thus contribute to the long-term international targets on implementation of renewable energy in the built environment.

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